GEOTHERMAL POWER PRODUCTION UTILIZING SUPERCRITICAL CO_2 COMBINED WITH DEEP EARTH CARBON SEQUESTRATION

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ABSTRACT

For equivalent levels of electric power production, a deep man-made geothermal reservoir designed to supply the heat requirements for power generation would sequester, per unit time, about as much CO_2 as that produced by a typical coal-fired power plant. The deep earth carbon sequestration would be accomplished by the gradual diffusion of CO_2 into the unfractured rock mass surrounding the highly pressurized geothermal reservoir.

INTRODUCTION

A new engineered geothermal energy concept using supercritical CO_2 ($SCCO_2$) to both create the man-made geothermal reservoir and for heat transport to the surface is here proposed. This concept builds on the extensive Hot Dry Rock (HDR) research and development effort conducted by Los Alamos National Laboratory (LANL) at Fenton Hill, NM. This previous field testing convincingly demonstrated the viability of the HDR heat-mining concept, based on the results obtained from the production testing of two separate confined reservoirs for almost a year each. However, using $SCCO_2$ instead of water in a closed-loop HDR system offers three significant advantages over the original Los Alamos concept:

- The very significant wellbore density difference between the cold $SCCO_2$ in the injection well (about 0.96 g/cc) and the hot $SCCO_2$ in the production wells (about 0.39 g/cc) would provide a very large buoyant drive (i.e., thermal siphoning), markedly reducing the circulating pumping power requirements over those of a comparable water-based HDR system.

- The inability of $SCCO_2$ to dissolve and transport mineral species from the geothermal reservoir to the surface would eliminate scaling in the surface piping, heat exchangers, and other surface equipment.

- HDR reservoirs at temperatures in excess of 374°C (the critical temperature for water) could be developed without the problems associated with silica dissolution in water-based systems, potentially providing increased thermodynamic efficiency for the surface power-conversion equipment.

Thermodynamic and systems analyses show that $SCCO_2$, because of its unique properties, is nearly as good as water when used for heat mining from a confined HDR reservoir (see Brown, 2000). Even though the mass heat capacity of $SCCO_2$ is only two-fifths that of water, for equivalent reservoir operating conditions, the ratio of fluid density to viscosity (a measure of the reservoir flow potential) is 1.5 times greater for $SCCO_2$ than for water, primarily due to the viscosity of $SCCO_2$ which is 40% that of water. Therefore, the rate of geothermal energy production using $SCCO_2$ would be about 60% that of water. However, on a net power production basis, when pumping power requirements are considered, the power production from an $SCCO_2$-HDR system would almost equal that of a water-based HDR system.

The commercial development of this new renewable energy concept, given the ubiquitous worldwide distribution of the HDR geothermal resource, could be a significant contributor to providing clean, renewable sources of energy for the 21st century. Further, this new geothermal energy concept would help in mitigating global warming since a supercritical-CO_2-based HDR system would also sequester significant amounts of CO_2 deep in the earth by fluid diffusion into the rock mass surrounding the reservoir. To put this statement in perspective: Such an HDR power plant, based on long-term reservoir pressurization/fluid-loss studies carried out by LANL at Fenton Hill, would have the capability of continuously sequestering, by fluid diffusion into the rock mass surrounding the HDR reservoir, about as much CO_2 as that produced by a typical coal-fired power plant, each on a per MW-electric generation basis [24 tons of CO_2 per day per MW(e)].

THE HOT DRY ROCK CONCEPT AND RESOURCE BASE

HDR geothermal energy, which utilizes the natural heat contained in the earth's crust, can provide a widely available source of nonpolluting energy. The earth's heat represents an almost unlimited source of indigenous energy that could begin to be exploited worldwide within the next decade through the LANL-developed heat-mining concept. The feasibility of this concept has already been demonstrated by LANL through a sequence of field experiments at the Fenton Hill HDR test site extending over more than 20 years.

As depicted in Figure 1, hydraulic fracturing techniques developed by the oil industry would be used to create a very large stimulated volume of hot crystalline rock containing significant artificial permeability. This permeability would be created by pressure dilating the multiply interconnected array of pre-existing -- but hydrothermally resealed -- natural joints and fractures contained in a previously almost completely impermeable rock mass. This hydraulically stimulated region (the HDR reservoir) would then be connected to the surface through a pair of *production* wells, forming a closed-loop circulating system to transport the geothermal heat to the surface to be used in heating a secondary working fluid in a Rankine power cycle, or alternatively, to be used nearby for direct heating applications. In effect, we would be mining heat in a fashion analogous to the way other earth resources are obtained, but without any attendant pollution since the only thing that would be produced in this closed-loop process would be heat.

Numerous estimates place the accessible HDR resource base somewhere between 10 and 13 million quads in the US, and over 100 million quads worldwide (Tester et al., 1989). Figure 2 provides estimates of the geothermal temperature gradient distribution across the US and clearly shows that the moderate-grade (30° to 45°C/km) HDR resource is well distributed. Kron and Heiken (1980) estimate the high-grade US HDR resource base, with gradients greater than 45°C/km, to be in excess of 650,000 quads. Thus, on almost any basis, the amount of potentially usable thermal energy in the HDR resource is vast -- literally orders of magnitude larger than the sum total of all fossil and fissionable resources (see Figure 3 for a resource comparison on a worldwide basis). Even if only a small fraction of the accessible HDR resource base is ultimately extracted, the impact on the US energy supply could be far-reaching.

PRIOR RESEARCH

During the period from 1974 through 1995, LANL was actively engaged in field-testing and demonstrating the Hot Dry Rock (HDR) geothermal energy concept at their Fenton Hill HDR test site in the Jemez Mountains of north-central New Mexico (Brown, 1995a). This testing ended with the very successful demonstration of sustained energy production from the deeper HDR reservoir during a series of flow tests referred to as the Long-Term Flow Test (LTFT), conducted from April 1992 through July 1995 (Brown, 1994 and 1995b). Although that program has now ended, a vast amount of information was obtained concerning the characteristics and performance of confined HDR reservoirs during this extended period of testing. For instance, a recent report (Brown, 1999) summarizes the data from the LTFT supporting the existence and long-term stability of a highly pressurized region of jointed rock at a depth of 3.6 km, which is quite germane to studying the deep sequestration of carbon dioxide in basement rock associated with an HDR geothermal power-production system.

THE $SCCO_2$-HDR CONCEPT

In this new concept for engineered geothermal reservoirs, which embodies much of the original HDR concept developed and demonstrated by LANL, $SCCO_2$ would be used for both the fracturing fluid and the heat transport fluid for deep-earth heat-mining systems. As envisioned, a three-well HDR system -- two production wells and one injection well -- would be employed to best access the fractured reservoir region (Brown and DuTeaux, 1997). As shown schematically in Figure 1, the heat contained in the hot geofluid would be transferred to a secondary working fluid in a high-pressure heat exchanger included as part of the surface power plant.

A major contributing factor to the enhanced performance of an $SCCO_2$-HDR system is the very significant buoyant drive across the reservoir, arising from the marked density contrast between the hot fluid rising in the production wells and the cold, much more dense fluid in the injection well. For example, for an appropriate set of $SCCO_2$ surface operating conditions for the HDR reservoir depicted in Figure 1 -- a mean injection pressure of 30 MPa at 40°C and a surface production backpressure of 30 MPa at 250°C, the mean fluid density in the injection wellbore would be 0.96 g/cc and the corresponding mean fluid density in the production wellbores would be 0.39 g/cc, providing a density difference of about 0.57 g/cc. At a reservoir depth of 4 km, this augmented buoyant drive provided by using $SCCO_2$ instead of water as the geofluid would add an additional 22 MPa (3200 psi) to the pressure differential driving fluid across the reservoir. For the case of laminar flow which is the accepted flow regime in HDR reservoirs, this would more than double the production flow rate compared to a water-based HDR system with the same reservoir flow impedance and injection pressure, potentially providing a thermal power potential exceeding that of an equivalent water-based HDR system.

RESERVOIR CREATION

The engineered HDR reservoir region, probably approaching an ultimate volume of 1/2 cubic kilometer or more, would be created by hydraulically fracturing a deep region of essentially impermeable, hot, crystalline rock using $SCCO_2$ instead of water as the fracturing fluid. This would be accomplished by pumping $SCCO_2$ from the surface down a high- pressure tubing string, and injecting this fluid into a packed-off (i.e., pressure-isolated) interval of openhole wellbore for a period of several weeks or more, at a rate in the range of 20 to 40 kg/s.

Initially, as the pressure in the packed-off interval rapidly increases, one or more of the more favorably oriented natural joints intersecting the wellbore would start to open under a combination of tensile (hoop) stresses at the wellbore surface and normal opening stresses from fluid invasion into the somewhat more permeable (than the adjacent rock) hydrothermally sealed natural joints. As pumping continues, these joints would progressively open and interconnect, forming a multiply connected region of pressure-dilated joints in the rock mass surrounding the packed-off wellbore interval, thus creating the fractured HDR reservoir.

Based on over 20 years of reservoir testing at Fenton Hill, NM, this opening of an array of natural joints is in stark contrast with the originally envisioned formation of one or more large, near-vertical, penny-shaped fractures created by hydraulic fracturing (Brown, 1995a). Based on the Laboratory's extensive experience with hydraulic fracturing of deep basement rock using water, there appears to be no limitation to using $SCCO_2$ for similar operations. It should be noted that hydraulic fracturing of sedimentary formations using $SCCO_2$, as reported by Yost et al. (1994), is now routinely done to increase the productivity of petroleum reservoirs where special reservoir conditions warrant this type of stimulation to minimize formation damage from water-based fracturing fluids.

POST-HYDRAULIC-FRACTURING FLUID COMPOSITION IN THE RESERVOIR REGION

From laboratory measurements on core samples of Precambrian crystalline rock obtained from depths between 1.2 and 2.8 km at Fenton Hill, a mean in-situ rock mass porosity of 0.9×10^{-4} has been determined (Simmons and Cooper, 1977). In contrast, following reservoir creation by hydraulic fracturing and the accompanying dilation of the pressure-stimulated array of joints, the mean reservoir porosity was about 1.2×10^{-3} [24,700 m^3 of water injected into a pressure-accessible volume of 20 million m^3 (Brown et al., 1999)]. Therefore, using an analogy to the deeper Fenton Hill HDR reservoir, the fracture volume occupied by the $SCCO_2$ would be about 13 times greater then the initial microcrack pore volume in the rock mass. For this situation, the $SCCO_2$ would tend to *dissolve* almost all of the original pore fluid (essentially a brine), with the mineral constituents previously dissolved in the pore fluid being left behind as mineral precipitates. Figure 4 shows the solubility, at 250°C, of water in $SCCO_2$ and $SCCO_2$ in water as a function of pressure. For an HDR reservoir with a rock temperature of 260°C at a depth of 4 km, and with a surface injection pressure of 30 MPa, one would anticipate about a 24 mol% solubility of water in $SCCO_2$. This solubility is equivalent to a 10% solubility by weight, which would imply that all the previously existing pore fluid within the microcrack pore structure of the rock would end up being dissolved by the $SCCO_2$ diffusing into the rock mass.

CO_2 SEQUESTRATION IN THE ROCK MASS SURROUNDING THE HDR RESERVOIR

Again, from experience gained from extensive field testing of the deeper HDR reservoir at Fenton Hill, the fluid loss from a 1/2 cubic kilometer pressure-stimulated reservoir volume, at a mean reservoir injection pressure of 30 MPa (4350 psi) above hydrostatic, is predicted to be about 3 kg/s for a 10-MW(e) power system, which is equivalent to 100,000 tons per year. Although not a very large number in absolute terms, over the predicted 20-year lifetime of a suitably engineered HDR reservoir, this diffusional loss of $SCCO_2$ into the rock mass immediately adjacent to the HDR reservoir would be very significant -- about 2 million tons of CO_2 sequestered deep in the earth for each 10-MW(e) HDR power plant. This is in addition to the 48,000 ton inventory of $SCCO_2$ circulating through the reservoir and the surface power plant for such a 10-MW(e) HDR power system.

This leads to an ancillary benefit at the periphery of the HDR fractured region, where the $SCCO_2$ would be slowly diffusing outward to the far field from the pressurized reservoir. In the surrounding rock mass, the pre-existing water-filled network of interconnected microcracks would be slowly flushed with $SCCO_2$, leaving behind mineral precipitates which would tend to slowly plug off the microcrack porosity and seal the reservoir boundaries over time -- which, from the normal point of view, are almost impermeable already (with a permeability in the range of several hundredths of a microdarcy).

SUMMARY AND CONCLUSIONS

In a confined reservoir, which is one of the unique characteristics of a true man-made HDR reservoir, as contrasted with a natural hydrothermal geothermal reservoir, the chemistry and/or nature of the circulating fluid can be specified by the operator (Brown et al., 1999). For this reason, the choice of $SCCO_2$ as the working fluid is possible, and alters considerably the potential for designing unique features into such engineered geothermal systems.

As an ancillary benefit from the standpoint of carbon sequestration, the slow diffusional loss of $SCCO_2$ from the pressurized HDR reservoir region outward into the surrounding unfractured -- and therefore *confining* -- rock would, over the long term, provide a considerable amount of carbon storage within the microcrack volume of this rock mass.

In this preliminary study of the $SCCO_2$-HDR concept, it was not possible to consider all the ramifications or nuances of using a geofluid other than water as the heat transport fluid in an engineered heat-mining concept. However, the advantages of using $SCCO_2$ in a power-producing man-made HDR geothermal system appear to be considerable.

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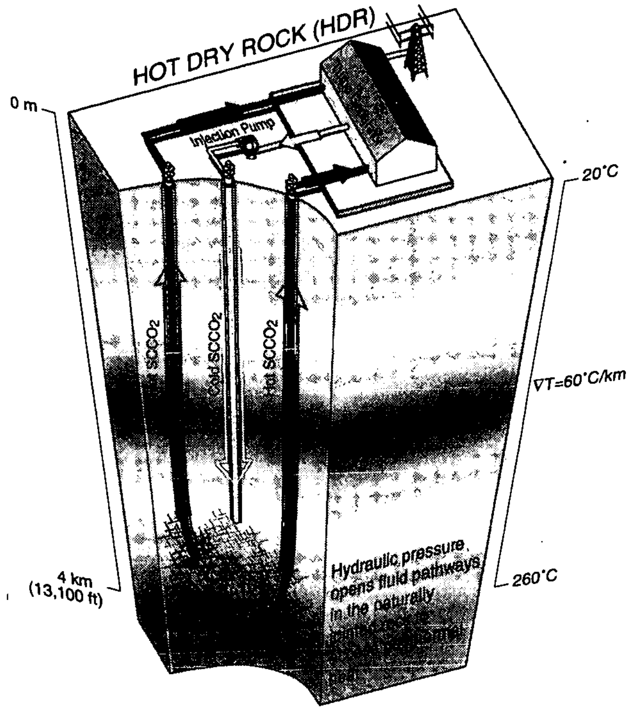

Figure 1: HDR–$SCCO_2$: A System Engineered for Geothermal Heat Mining Using Supercritical CO_2.

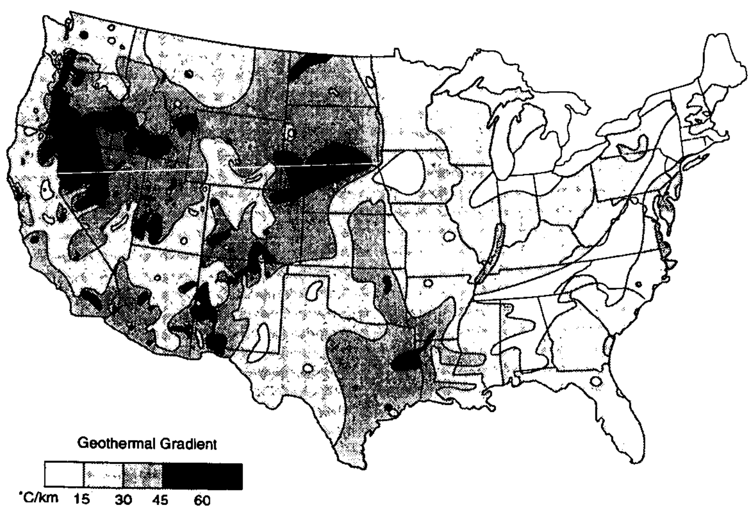

Figure 2: The Distribution of Geothermal Temperature Gradients in the "Lower 48" States.

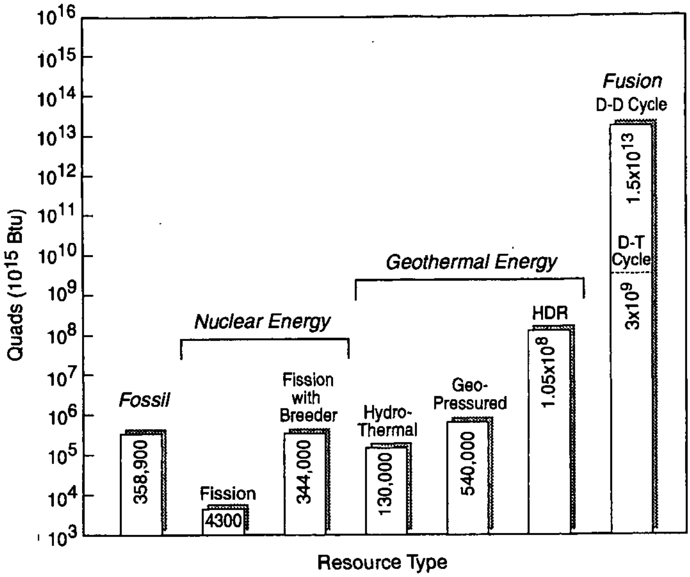

Figure 3: Worldwide nonrenewable resources.

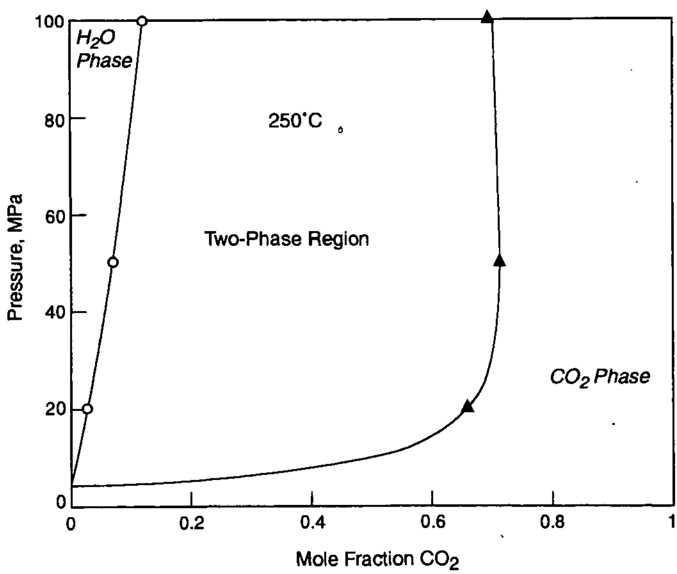

Figure 4: Phase diagram for $CO_2 + H_2O$ at 250°C. Adapted from Shyu et al. (1997).